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Exergy analysis of solar energy applications

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ABSTRACT

Solar energy is a clean, abundant and easily available renewable energy. Usage of solar energy in different kinds of systems provides scope for several studies on exergy analysis. In the present work, a comprehensive literature review has been carried out on exergy analysis of various solar energy systems. The systems considered under study are solar photovoltaic, solar heating devices, solar water desalination system, solar air conditioning and refrigerators, solar drying process and solar power generation. The summary of exergy analysis and exergetic efficiencies is presented along with the exergy destruction sources.

Contents

1. Introduction

Development of renewable energy sources as a replacement of fossil fuels had been taken into consideration in past few decades [1,2]. Solar energy as an available, cheap and environmental friendly alternative source has been the subject of many theoretical and experimental studies [3]. The integration of solar energy with different kinds of systems plays an important role in energy saving policy. In case of combining the photovoltaic and solar thermal components, both heat and electricity can be produced from the same system. It is widely known that a solar heating device has a significant role in reducing the energy consumption. Applying solar energy in desalination process is a clean option to provide drinking water from saline water.

Exergy analysis evaluates the efficient usage of solar energy. By determining the sources and magnitude of irreversibilities, exergy analysis can be used to improve the efficiency of a system. Number of studies has been conducted in performance evaluation of different systems in residential [4], commercial [5,6], industrial [7–9] and transportation sectors [10]. Investigators such as [11,12] have performed exergy analysis of refrigeration cycle. Exergy analysis is employed in different fields of solar heating devices [13–15], solar water desalination [16,17], solar air conditioning and refrigeration systems [18], solar drying process [19,20] and solar power generation [21].

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Nomenclature

A	area (m^2)
C_p	heat capacity (kJ/kg K)
$\dot{E}x_{in}$	exergy input
$\dot{E}x_{out}$	exergy output
$\dot{E}x_{work}$	exergy of work rate
$\dot{E}x_{thermal}$	exergy of thermal energy
$\dot{E}x_{Ch}$	chemical exergy
$\dot{E}x_k$	kinetic exergy
$\dot{E}x_p$	potential exergy
$\dot{E}x_{phy}$	physical exergy
HPVT	hybrid photovoltaic thermal
$I(t)$	incident solar intensity (w/m^2)
MCPVT	micro channel photovoltaic thermal
MCSCT	micro channel solar cell thermal
PV/T	photovoltaic thermal
PV	photovoltaic
η_{th}	thermal efficiency
η_{exergy}	exergy efficiency
η_0	efficiency at standard test condition
ε	exergetic efficiency

The above-mentioned solar energy systems are often used for various purposes. Therefore, the studies on exergy analysis and exergetic efficiencies of these systems are highly desirable. Within the present study, the performance analysis of solar energy application based on the second law of thermodynamic is reviewed and classified. The present review of existing literature also gives a comprehensive idea of various sources involved in exergy destruction. To the best of authors' knowledge, there is no work on the review of exergy analysis of above discussed solar energy systems. Therefore, this review shall help in filling this gap.

2. Studies conducted on exergy analysis of solar energy

The Section 2.1 discusses the review of exergy analysis of solar photovoltaic application. The solar photovoltaic as the direct convertor of sunlight to electrical energy were taken into account during the last decades. Being clean and renewable, the solar PV cells were applied in different sectors of residential, industrial and commercial. The review of exergy analysis of solar ponds applications is described in Section 2.2. Solar ponds are used to collect and store solar energy in order to supply the required thermal energy of different processes.

2.1. Exergy analysis of solar photovoltaic

Development of the ratio between the electrical and thermal output of a domestic style PV/T system had been done by Coventry and Lovegrove [22]. The ratio between the thermal energy and the electricity was introduced as a dimensionless factor, which can affect the design, and energy cost of the PV/T system. This dimensionless factor was evaluated as 1.0 based on the first law analysis, and it changed to 17 by applying the exergy analysis and second law of thermodynamics. The effect of this ratio on optimum design of system was demonstrated by an example.

The exergetic efficiency of a hybrid PV/T air collector was evaluated in a study by Joshi and Tiwari [23]. In order to analyse the energy and exergy of optimum inclination, they had determined the condition under which the solar gain was maximum. The exergetic efficiency of the PV/T air collector was calculated based on Eq. (1):

$$\eta_{exergy\,overall} = \eta_0[1-\beta\Delta T] + \eta_{th}\left[1-\frac{T_0+273}{293+\Delta T}\right] \quad (1)$$

The calculated exergy efficiency was varied between 12–15% in January and 13–14% in June. They had also pointed out that the monthly total amount of exergy varies between 8 kWh and 15 kWh. By investigating the effect of flow rate on the yearly amount of exergy, it was found that increasing the flow rate leads to exergy increment.

The exergy analysis of PV/T integrated with a solar greenhouse had been done by Nayak and Tiwari [24]. They considered the yearly exergy input as a combination of the radiation exergy on the south roof and on the PV module. The exergy input for PV module was obtained using Eq. (2) [25]:

$$\dot{E}x_{in} = A_C \times I(t)\left[1-\frac{4}{3}\left(\frac{T_a+273}{T_S}\right)+\frac{1}{3}\left(\frac{T_a+273}{T_S}\right)^4\right] \quad (2)$$

By substituting A_C and I_C with A_{sr} and I_{sr} the exergy input of south roof was calculated. They evaluated the exergy output of greenhouse based on the study conducted by Syahrul et al. [26], which is expressed by Eq. (3).

$$\dot{E}x_{th,daily} = \sum\left(1-\frac{T_a+273}{T_r+273}\right)\times\dot{Q}\ u_{daily} \quad (3)$$

The defined exergy efficiency is given by Eq. (4).

$$\eta_{Ex} = \left(\frac{\dot{E}x_{out}}{\dot{E}x_{in}}\right)\times 100 \quad (4)$$

The total yearly exergy was reported to be 12.8 kWh and the calculated exergetic efficiency of the PV/T integrated greenhouse was found to be 4%.

The exergetic and economic analysis of Hybrid Photovoltaic Thermal (HPVT) were carried out by Raman and Tiwari [27]. The study was conducted for four different cities of India. The annual exergy output was calculated based on Eq. (5) which was applied by Bosonac et al. [28].

$$E_{aex} = \dot{Q}_u\left[1-\frac{25+273}{T+273}\right] \quad (5)$$

The maximum reported exergy output was 157.22 kWh and the maximum exergy efficiency of the considered cities ranged from 11.4% to 14.8%. Comparing the thermal efficiency and the exergy efficiency, they had found that the exergy efficiency is about 40% lower than the thermal efficiency.

The performance of the PV/T flat plate water collector which was considered to be in series pattern had been evaluated in four different weather conditions of India [29]. The total exergy inflow was calculated based on Eq. (2). The exergy outflow was considered to be a combination of thermal and electrical exergy. Six collectors connected in series pattern with constant mass flow rate were investigated. They found that the amount of total exergy is maximum in summer. The annual exergy was 1273.7 kWh.

A comparison between the exergy efficiency of PV/T collector with or without glass cover was done by Chow et al. [30]. Both cases were modelled numerically and the results were validated using one day collected data. The overall exergetic efficiency was considered as the sum of exergetic efficiency of thermal collector and the PV cells. It is given by Eq. (6).

$$\varepsilon_{PVT} = \eta_{PV} + \left(1-\frac{T_a}{T_2}\right)\eta_t \quad (6)$$

where T_a and T_2 represents the ambient temperature and the final temperature of the fluid medium respectively. The exergetic efficiency was defined as the ratio of total exergy outflow to the total

exergy inflow. They found that the desired parameters for the exergetic efficiency of PV cells were unfavourable for the thermal exergy efficiency. They also pointed out that the exergy efficiency for unglazed condition is better in comparison with the glazed condition.

An analytical expression was derived for the PV/T collectors connected in series [31]. The performances of two different air collectors fully covered with the PV module were compared. In one air collector air flowed over the absorber plate and in another one the airflow was below the plate. The exergy balance of both configurations was analysed. It was concluded that in case of electricity generation and hot air production the configuration in which air flow was below the absorber plate is much more better.

Exergy efficiency of a typical PV/T air collector was assessed and a detailed exergy analysis along with computer simulation was presented [32]. They used the general form of the exergy balance, which can be expressed as Eq. (7) [33].

$$\dot{E}x_{fin} - \dot{E}x_{ini} = \dot{E}x_Q - \dot{E}x_W + \dot{E}x_{in} - \dot{E}x_{out} - \dot{I}_{c.v} \tag{7}$$

The exergy rate of inlet mass to control volume was calculated using Eq. (8).

$$\dot{E}x_{in} = \dot{m}C_p\left[T_{f,in} - T_{anb} - T_{amb}\ \ln\left(\frac{T_{f,in}}{T_{amb}}\right)\right] + \dot{m}RT_{amb}\ \ln\left(\frac{T_{f,in}}{P_{amb}}\right) \tag{8}$$

The exergy rate of outlet mass was calculated by changing the parameters of inlet with the parameters of outlet in above equation. The exergy rate of heat transfer was evaluated using Eq. (2). Eq. (9) is used to calculate the work exergy rate [34].

$$\dot{E}x_W = V_{mp}I_{mp} = \dot{E}_{el} \tag{9}$$

The irreversibility rate was assumed to be the combination of external exergy losses and internal exergy destruction [35]. Finally, the exergetic efficiency of the system was obtained by Eq. (10).

$$\eta_{ex} = 1 - \left(\frac{\dot{E}x_{los} + \dot{E}x_{dex}}{\dot{E}x_{Q,sun}}\right) \tag{10}$$

The obtained results of the simulation were verified with the experimental results by Joshi et al. [36]. They studied the effect of various parameters such as inlet air temperature, air velocity, solar radiation intensity and wind speed on the exergy efficiency.

An evaluation of the performance of hybrid Micro Channel Photovoltaic Thermal (MCPVT) based on the second law of the thermodynamics was done by Agrawal and Tiwari [37]. The data was collected in four different weather conditions of India. The exergy components were calculated based on existing formulas in the literature. It was reported that the maximum monthly overall exergy efficiency of 18% occurred in January. The minimum amount (15.8%) was recorded in June. They also compared the exergetic efficiency of Micro Channel Solar Cell Thermal (MCSCT) with the MCPVT. It was found that the overall exergy efficiency of the MCPVT is higher than MCSCT.

Table 1 shows the exergy efficiency of solar collectors under study.

Table 1
Exergy efficiency of solar collectors [32].

No.	Solar collector system	Exergy efficiency	Ref.
1	The glazed PV/T water collector	13.30%	[38]
2	The coverless PV/T water collector	11–12.87%	[39]
3	The unglazed PV/T air collector	10.75%	[32]
4	The (glass-to-glass) PV/T air collector	10.45%	[31]
5	The glazed PV/T water collector	8–13%	[28]
6	The PV array	3–9%	[34]
7	The unglazed PV/T air collector integrated greenhouse with earth air heat exchanger	5.50%	[40]
8	The unglazed PV/T air collector integrated greenhouse	4%	[24]
9	The double glazed flat-plate water collector	3.90%	[41]
10	The BIPV/T air collector	2.12%	[42]
11	The double glazed air heater	2%	[43]

2.2. Exergy analysis of solar ponds

The supplied thermal energy through the solar ponds can be used for different applications of heating, water desalination, air conditioning and refrigeration, industrial drying, etc. Solar heating devices are utilized the solar energy to heat the air and water. Solar desalination process is considered as a clean option to reduce the salinity of the seawater in order to convert it into drinking water. Integrating the solar energy and air conditioning process made the cooling system environmentally safe and energy efficient. The solar energy is applied in industrial drying process in order to remove maximum moisture from the products. The detail review of exergy analysis of solar ponds application is discussed in below sections.

2.2.1. Exergy analysis of solar heating devices

The performance of solar water heating systems for building application was evaluated by Gunerhan and Hepbasli [44]. Exergy efficiency was calculated using Eq. (11) [45]:

$$\varepsilon = 1 - \frac{Ex_{dest}}{Ex_{input}} \tag{11}$$

The solar collector exergy efficiency is defined as the ratio of increased water exergy to the exergy of solar radiation. It was represented by Eq. (12).

$$\varepsilon_{col} = \frac{\dot{E}x_u}{\dot{E}x_{scol}} \tag{12}$$

where the useful exergy and the absorbed exergy of solar collectors were computed by Eqs. (13) and (14), respectively.

$$\dot{E}x_u = \dot{m}_W[(h_{W,out} - h_{W,in}) - T_0(S_{W,out} - S_{W,in})] \tag{13}$$

$$\dot{E}x_{scol} = AI_T\left[1 + \frac{1}{3}\left(\frac{T_0}{T_{sr}}\right)^4 - \frac{4}{3}\frac{T_0}{T_{sr}}\right] \tag{14}$$

It was concluded that the highest exergy destruction was due to solar collector. The exergy destruction was 95%. The solar exergetic efficiency of was reported as 16.17%.

A mathematical model of direct expansion solar assisted heat pump system was presented by Kara et al. [46]. The model was evaluated by an illustrative example. Solar collector acts as evaporator in the modelled heat pump system. They had applied the general energy and exergy efficiencies given in the literature [47]. It was concluded that the maximum exergy losses occurred in compressor, which was followed, by the condenser and solar collector. The exergy efficiency of solar collector was reported to be 23.81%.

The exergy base performance of solar assisted heat pump was evaluated by Dikici et al. [48]. Dividing the exergy into four components of physical, chemical, kinetic and potential, they had found that the most effective component in heat pump cycle is physical exergy [49]. To detect higher exergy destruction the exergy efficiency was applied to each device of the system. It was found that exergy loss of the solar collector was 1.92 kW. The second law efficiency of the system was obtained as 30.8%.

Three different types of flat plate solar air heaters, with or without fin were compared by Alta et al. [50]. The ratio of the gained exergy to the input exergy was defined as the exergetic efficiency of

Table 2
Summary of reviewed papers for exergy analysis of solar heating devices.

No.	Heating device	Exergy efficiency	Key results	Ref.
1	Solar water heating system	16.17%	The highest exergy destruction was related to the solar collector	[44]
2	Solar assisted heat pump	23.81%	It was concluded that the maximum exergy losses occurred in compressor, which was followed, by the condenser and solar collector	[46]
3	Solar assisted heat pump	30.80%	The exergy losses of solar collector was found to be 1.92 kW	[48]
4	Flat plate solar air heaters		It was concluded that the solar air heaters with fins are more efficient than those without fins	[50]
5	Flat plate solar heaters	44%	It was found that as the air mass flow rate and time increases the exergetic efficiency also increases	[52]

the system which was also applied by Kaushik et al. [51]. The highest reported exergy efficiency (0.834%) belonged to double glass cover flat plate air heater with fins. It was concluded that the solar air heaters with fins are more efficient than those without fins.

On the basis of the thermodynamics laws, the performance of four different absorbing plates of flat plate solar heaters were compared [52]. Same method developed by Esen [53] was applied to do the analysis. Exergy balance was calculated as per Eq. (15) based on some the assumptions [54,55]:

$$\dot{E}x_{dest} = \left(1 - \frac{T_e}{T_S}\right)\dot{Q}_s = \dot{m}[(h_{out} - h_{in}) = T_e(S_{out} - S_{in})] \quad (15)$$

The effect of air mass flow rate, time and temperature on the second law efficiency of the solar collector was evaluated. It was found that as the air mass flow rate and time increases the exergetic efficiency also increases. The maximum exergy efficiency obtained was 44%.

A summary of key findings in exergy analysis of solar heating devices are presented in Table 2.

2.2.2. Exergy analysis of solar water desalination

The exergy analysis of solar multi effect humidification and dehumidification desalination process was carried out by Hou et al. [17]. Eq. (16) presents the exergy balance.

$$\dot{S} = \dot{L}_{ex,collector} + \dot{L}_{ex,h} + \dot{L}_{ex,d} + \dot{E}x_{saline\,water} \quad (16)$$

The exergy efficiency of solar collector was defined as the ratio of collector exergy rate to the total exergy rate of the system. It was concluded that the solar collector exergy efficiency was 86% whereas the exergy efficiency of the humidifying process was reported 91%.

The exergy efficiency and the exergy destruction of solar powered membrane distillation unit was investigated by Banat and Jwaied [56]. They adopted the exergy analysis study of Kahraman et al. [57] to determine the efficiencies of each component and to improve the total efficiency of the desalination unit. The calculated second law efficiency of the system was reported in range of 3–6.5%. They concluded that the exergy efficiency of the compact system was little higher than the large system. The membrane distillation was detected as the major source of exergy losses.

The exergy analysis of a combination of a solar collector, heat transformer and desalination unit was done by Gomri [16]. The exergy was considered as a summation of physical and chemical exergy. The effect of kinetic and potential exergy was neglected. The specific exergy was computed using Eq. (17) considering chemical exergy zero as it was suggested by Vidal et al. [58].

$$ex = (h - h_0) - T_0(s - s_0) \quad (17)$$

The exergetic efficiency was calculated using Eq. (18) [59,60]

$$\eta_{ex} = \frac{\text{Exergy produced}}{\text{Exergy used}} \quad (18)$$

Substituting the exergy produced and exergy used, in the general formula the total exergy efficiency of the system was expressed by Eq. (19).

$$\eta_{ex} = \frac{Q_{ab}[1 - (T_0/T_{ab})]}{[I_G \cdot A_C \cdot N_C(1 - (T_0/T_S)) + W_{pumps}]} \quad (19)$$

Based on the changed pattern of exergy destruction during the experimental test, they had approved the dependence of exergy destruction and the amount of solar radiation. The flat plate collector was detected as the component with the highest exergy loss.

2.2.3. Exergy analysis of solar air conditioning and refrigeration

Based on the thermodynamics laws, the optimum operating conditions of solar driven ejector refrigeration system was found by Pridasawas and Lundqvist [61]. The considered refrigeration cycle consisted of an ejector, a condenser, a generator, an evaporator, a pump and the expansion device. The exergy balance for this system was given by Eq. (20).

$$E_{S,h} + E_e + W_{p,el} = E_{c,out} + I_{total} \quad (20)$$

where the exergy of solar heat input was computed by formula developed by Izquierdo et al., which is shown in Eq. (21) [62].

$$E_{S,h} = Q_{avg}\left(1 - \frac{T_{ref}}{T_{SC}}\right) \quad (21)$$

The ratio of exergy of the ejector to the exergy of the pump and generator was defined as the exergetic efficiency. The exergy efficiency of solar collector was reported to be 0.66% and the solar collector was found to be the main source of irreversibility.

Onan et al. [63] conducted a survey on exergy analysis of a solar assisted absorption cooling system. They had computed the calculation based on two different dead states of standard temperature and environment temperature. Applying the formula developed by Banat and Jwaied [56] the second law efficiency of solar collector was calculated. The maximum amount of efficiency was found to 11.98%. The general form of exergy was expressed as per Eq. (22) [20].

$$\sum\left(1 - \frac{T_\infty}{T}\right)\dot{Q} - \dot{W} + \sum \dot{m}_i\psi_i - \sum \dot{m}_o\psi_o = \dot{E}x_{dest} \quad (22)$$

They also concluded that the major part of the exergy destruction occurred in solar collectors, which was then followed by generator of absorption chillers.

Koroneos et al. [18] investigated the performance of solar air conditioning system by application of exergy analysis. The exergy efficiency of the system was computed using Eq. (23).

$$\eta = 1 - \frac{\Sigma X_{lost}}{\Sigma X_{in}} \quad (23)$$

where the total exergy input and total exergy lost of the system was calculated by Eqs. (24) and (25), respectively.

$$X_{in} = \sum m_i x_i - \sum Q\left(1 - \frac{T_0}{T}\right) i + \sum w \tag{24}$$

$$\sum X_{lost} = \sum T_0 S_{gen} = T_0\left[\left(m(S_2 - S_1) - \frac{Q}{T}\right)\right] \tag{25}$$

They compared the results obtained by Sencan et al. [64]. The results were found to be in good agreement. They also determined the generator and absorber as the main sources of exergy destruction. It was also concluded that exergy efficiency decreases by raising the temperature of heat source.

2.2.4. Exergy analysis of solar drying process

Midilli and Kucuk [65] conducted a study on exergy analysis of shelled and unshelled pistachios by utilizing a solar drying cabinet. Assuming some simplifications Eq. (26) was used to calculate the exergy [66].

$$\text{Exergy} = c_p\left[(T - T_\infty) - \frac{T_\infty \ \ln T}{T_\infty}\right] \tag{26}$$

The equation of exergy outflow was written for each shelf of the dryer cabinet. They performed thirteen experiments keeping drying duration and ambient temperature as variable. The maximum exergy input was reported to be 3.72 kJ/kg at ambient temperature of 32 °C. It was observed that by increasing the inlet temperature the exergy inflow of the cabinet increased linearly. Based on daily solar radiation, during first 2 h of the experiments the exergy inflow increased. Solar drying of the shelled pistachios was obtained the highest exergy efficiency in comparison with the unshelled pistachios.

The exergy analysis of olive mill wastewater solar drying process was considered by Celma and Cuadros [19]. To achieve the desired data for energy and exergy analysis they carried out number of experiments on their designed model. The assumed total exergy included physical, chemical, kinetic and potential exergy [67]. They applied the general form of total exergy equation, which depends on inlet and outlet temperature of the drying chamber. It is given by Eq. (27).

$$\dot{E} = \dot{m}_{da} c_p\left[(T - T_0) - T_0 \ \ln \frac{T}{T_0}\right] \tag{27}$$

The exergetic efficiency was calculated using Eq. (28) which was also applied by Akpinar et al. [68].

$$\varepsilon = 1 - \frac{\dot{E}_l}{\dot{E}_i} \tag{28}$$

The experiment was conducted for two days. The maximum input exergy was found to be 0.345 kJ/kg and 0.272 kJ/kg for the first and second day respectively. They also pointed out that by increasing the inlet temperature the exergetic efficiency decreases. The variation of exergetic efficiency with respect to drying time was also investigated.

Applying the first and second law of thermodynamics, the energy and exergy analysis of forced solar drying process of mulberry had been studied by Akbulut and Durmus [69]. During this drying process, the moisture content of the mulberry was decreased from 80% to 8%. They applied the same equation which was used by Celma and Cuadros [19] to compute the exergy inflow, exergy outflow and the exergetic efficiency. The effect of inlet temperature and drying period on the exergy loss and consequently on the exergetic efficiency was investigated. They pointed out that decreasing the temperature difference between inlet and outlet section, resulted in increment of exergy efficiency. It was also found that increasing the mass flow rate leads to decrement of drying time.

Akpinar [70] conducted a study on modelling and performance analysis of solar drying process of mint leaves. The general exergy balance was evaluated using Eq. (29) [20].

$$\sum\left(1 - \frac{T_\infty}{T}\right)\dot{Q} - \dot{W} + \sum \dot{m}_i \psi_i - \sum \dot{m}_o \psi_o = \dot{E}x_{dest} \tag{29}$$

The calculated exergy efficiency of the cabinet depends on daily solar radiation, changed from 34.76% to 87.71%. There was no significant difference observed in quality of dried leaves when compared with forced solar drying and open sun drying.

2.2.5. Exergy analysis of solar power generation

The performance of the solar thermal aided coal-fired power plants, based on the energy and exergy analysis was investigated by Suresh et al. [21]. The study also includes environmental and economical analysis. The plant exergy efficiency was defined based on Eq. (30).

$$\varepsilon = \frac{\text{Net electricity output}}{\text{Mass flow rate of coal} \times \text{specific exergy of coal}} \tag{30}$$

They also applied Exergy Performance Index (ExPI) which is calculates using Eq. (31).

$$\text{ExPI} = \frac{\text{Excess power generated over the design rated capacity}}{\text{Exergy input through solar irradiation}} \tag{31}$$

where the term of exergy input of solar radiation was computed by applying Eq. (32) [71].

$$\dot{E}x_s = \left[1 - \frac{4T_a}{3T_S}(1 - 0.28 \ \ln f\right]\dot{Q}_S \tag{32}$$

The plant exergy efficiency was reported in the range of 33.6–38.2%. By comparing the energy and exergy analysis, they found that the application of solar energy for feed water heating is more efficient based on the exergy analysis rather than energy analysis.

The exergy analysis of ammonia based solar thermochemical system was investigated by Lovegrove et al. [72]. The total exergetic efficiency was reported to be 70.7%. The reaction and heat transfer were found to be the two main sources of the irriversibilities.

3. Future directions

A comprehensive literature review shows many vital areas for further research. Following are important aspects required to be addressed for future work in this area.

1. In most of the studies the location and magnitude of exergy destruction was reported. The information regarding decrease or elimination of exergy losses is scanty.
2. An exergy analysis of heating devices with other kind of collectors rather than bare flat plate collectors could be a good research area for further studies. There are a few paper which studied glass covered and selective surface collectors integrated with heating devices.

4. Conclusions

Following conclusions summarizes the important findings.

1. Comparing the thermal efficiency and exergetic efficiency of the systems it can be concluded that thermal efficiency is not sufficient to choose the desired system.
2. The studied effective parameters on the exergy efficiency were mostly mass flow rate, inlet temperature and time.

3. The highest exergy destruction was observed in solar collectors in most of the solar heating devices and solar air conditioning systems.
4. Membrane distillation was found to be the major source of irreversibility in solar desalination process.
5. Increasing the mass flow rate leads to an increment in exergetic efficiency in photovoltaic thermal systems.
6. Exergy efficiency of solar systems is highly dependent on the daily solar radiation and radiation intensity.

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